

Spin-squeezing of a large-spin system via QND measurement

R.J. Sewell,^{1,*} M. Koschorreck,^{1,2} M. Napolitano,¹ B. Dubost,^{1,3} N. Behbood,¹ and M.W. Mitchell^{1,4}

¹*ICFO-Institut de Ciències Fotoniques, Av. Carl Friedrich Gauss, 3, 08860 Castelldefels, Barcelona, Spain.*

²*Cavendish Laboratory, University of Cambridge,*

JJ Thompson Avenue, Cambridge CB3 0HE, United Kingdom.

³*Univ. Paris Diderot, Sorbonne Paris Cité, Laboratoire Matériaux et Phénomènes Quantiques, UMR 7162, Bât. Condorcet, 75205 Paris Cedex 13, France*

⁴*ICREA-Institució Catalana de Recerca i Estudis Avançats, 08015 Barcelona, Spain*

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We demonstrate spin squeezing and entanglement in a large-spin system via quantum non-demolition measurement. We make non-destructive, projection-noise-limited collective spin measurements on an ensemble of up to in 8.4×10^5 laser-cooled ^{87}Rb atoms in the $f = 1$ hyperfine ground state. A dynamically-decoupled probing scheme [Phys. Rev. Lett. **105**, 093602 (2010)] prevents probe-induced decoherence, and techniques for compensation of magnetic field gradients [APL **98**, 074101, (2011)] extend the lifetime of the coherent spin state to 290 μs . Repeated measurements show correlations beyond the standard quantum limit, indicating generation of a spin-squeezed state with up to -3.2 dB of noise reduction and -1.8 dB of metrologically-relevant squeezing.

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Spin-squeezed states [1, 2], macroscopic entangled states with reduced quantum fluctuations, are of both fundamental and practical interest. Through spin-squeezing inequalities, collective (and thus macroscopic) observables imply underlying microscopic entanglement [3, 4]. Spin squeezing has produced multi-partite entanglement of over 100 particles [5], far more than has manipulation of individual particles. In quantum information, spin squeezed states appear in quantum memory protocols, where they can in principle be used to achieve perfect, deterministic storage and readout [6]. In quantum metrology [7], they can improve the sensitivity of atomic instruments such as atomic clocks [8, 9] and optical magnetometers [10, 11].

Spin squeezing has been demonstrated via the absorption of squeezed light [12], two photon transitions in ions [13, 14], the manipulation of the internal states of atoms with large spin [15, 16], atomic collisions in degenerate quantum gases [5, 17–19], quantum non-demolition (QND) measurement [20–23], and effective light-mediated interactions [24]. These results all concern real or effective spin-1/2 systems. Large-spin ensembles offer metrological advantage in magnetometry [25], and are essential for the study of quantum magnetism and exotic quantum phases in spinor Bose and Fermi gases [26–29]. For metrological applications, QND measurement has the advantage of allowing continuous measurements of macroscopically large atomic ensembles, with demonstrated advantage in high-bandwidth magnetometry [30].

In this manuscript, we report the first demonstration of spin squeezing in a large-spin ($f > 1/2$) atomic ensemble via QND measurement, following the strategy pioneered by Kuzmich and co-workers [31]. We pay careful attention to calibrating the spin-noise in our measurement, which has been a technical challenge in large-spin sys-

tems [25], and to extending the coherence lifetime of the magnetically sensitive coherent spin state (CSS). We observe a conditional spin noise reduction of -3.2 dB compared to the initial coherent spin state, and infer -1.8 dB of metrologically significant spin squeezing.

Optical QND of large-spin atoms.— We work with an ensemble of $f = 1$ atoms interacting with pulses of near-resonant polarized light. As described in references [32–34], the light and atoms interact by the effective Hamiltonian \hat{H}_{eff}

$$\tau \hat{H}_{\text{eff}} = G_1 \hat{S}_z \hat{J}_z + G_2 (\hat{S}_x \hat{J}_x + \hat{S}_y \hat{J}_y), \quad (1)$$

where τ is the duration of the pulse and $G_{1,2}$ are coupling constants that depend on the beam geometry, excited-state linewidth, laser detuning, and the hyperfine structure of the atom. The atomic variables $\hat{\mathbf{J}}$ are collective spin operators $\hat{J}_k \equiv \sum_i^{N_A} \hat{j}_k^{(i)}$ where the superscript indicates the i -th atom, and $\hat{j}_x \equiv (\hat{f}_x^2 - \hat{f}_y^2)/2$, $\hat{j}_y \equiv (\hat{f}_x \hat{f}_y + \hat{f}_y \hat{f}_x)/2$ and $\hat{j}_z \equiv \hat{f}_z/2$. For $f = 1$, these obey commutation relations $[\hat{j}_x, \hat{j}_y] = i\hat{j}_z$ and cyclic permutations. The light is described by the Stokes operators $\hat{\mathbf{S}}$ defined as $\hat{S}_i \equiv \frac{1}{2}(\hat{a}_+^\dagger, \hat{a}_-^\dagger) \sigma_i (\hat{a}_+, \hat{a}_-)^T$, where the σ_i are the Pauli matrices and \hat{a}_\pm are annihilation operators for the temporal mode of the pulse and circular plus/minus polarization.

The G_1 term in Eq. 1 describes a QND interaction (paramagnetic Faraday rotation) while the G_2 term describes a rank-2 tensorial atom-light coupling. For spin-1/2 atoms the G_2 term vanishes identically and Eq. 1 describes a pure QND measurement. However, for $f \geq 1$ atoms the G_2 term spoils the QND interaction even in the large-detuning limit [35, 36]. To recover the ideal QND interaction, we use a two-polarization probing technique based on dynamical decoupling methods, described

in detail in Ref. [36]. Briefly, we use a composite pulse sequence of alternating orthogonal polarizations of light, $\langle \hat{S}_x^{(v)} \rangle = -\langle \hat{S}_x^{(h)} \rangle = N_L/2$, such that, for an input \hat{J}_x -aligned CSS, the effect of the G_2 term is cancelled to first order. For weak pulses, i.e. $\langle \hat{S}_x \rangle$ sufficiently small, the system variable \hat{J}_z and meter variable \hat{S}_y after the two pulses are

$$\hat{J}_z^{(\text{out})} = \hat{J}_z^{(\text{in})} \quad (2)$$

$$\hat{S}_y^{(\text{out})} = \hat{S}_y^{(\text{in})} + 2G_1 \hat{S}_x^{(\text{in})} \hat{J}_z^{(\text{in})}, \quad (3)$$

where $\hat{S}_y' \equiv \hat{S}_y^{(v)} - \hat{S}_y^{(h)}$.

We define a normalized measurement variable $\hat{\phi} \equiv \hat{S}_y^{(\text{out})}/2G_1 \hat{S}_x^{(\text{in})}$, corresponding to the scaled rotation angle of the input light polarization, so that $\hat{\phi} = \hat{\phi}_n + \hat{J}_z^{(\text{in})}$, where $\hat{\phi}_n$ contains the electronic and light noise contributions to the measurement. A projection-noise limited measurement of the \hat{J}_z leads to a conditionally spin squeezed state. The quantum noise reduction can be estimated from two successive measurements of $\hat{\phi}$: the outcome, ϕ_1 , of the first measurement allows us to predict the outcome, ϕ_2 , of a successive measurement with an accuracy given by the measurement uncertainty. The best estimate for ϕ_2 is $\chi\phi_1$, where $\chi = \text{cov}(\phi_1, \phi_2)/\text{var}(\phi_1)$ is the correlation between the two measurements. The conditional variance, $\text{var}(\hat{J}_z|\phi_1) \equiv \text{var}(\phi_2 - \chi\phi_1)$, then quantifies the noise reduction [37].

Experiment.— We use the two-polarization probing technique to perform a QND measurement on an ensemble of up to 8.4×10^5 laser cooled ^{87}Rb atoms in the $f = 1$ ground state. In the atomic ensemble system, illustrated in Fig. 1(a) and described in detail in Ref. [38], μs pulses interact with an elongated atomic cloud held in an optical dipole trap and are detected by a shot-noise-limited polarimeter. The trap geometry produces a large atom-light interaction for light propagating along the trap axis. In earlier experiments we have measured

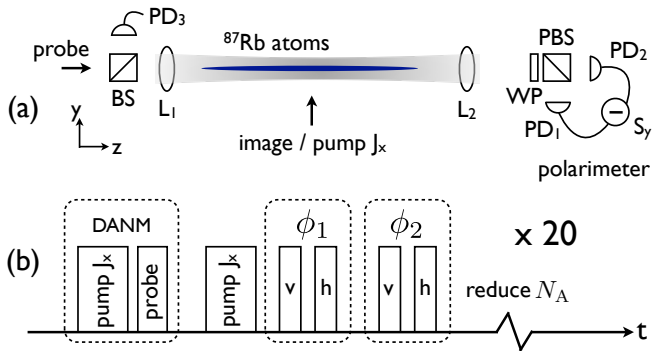


FIG. 1. (a) Experimental geometry. PD: photodiode; L: lens; WP: waveplate; BS: beam-splitter; PBS: polarizing beam-splitter. (b) Measurement pulse sequence. See text for details.

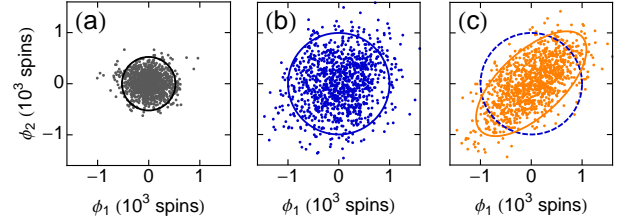


FIG. 2. Joint probability distribution of successive measurements of $\hat{\phi}$ with (a) no atoms in the trap, i.e. read-out noise, (b) independent CSS preparations, and (c) a single CSS preparation. Solid curves indicate 2σ radii for gaussian fits. Dashed blue circle in (c) reproduces solid circle in (b). Note: for presentation purposes, a small mean offset has been subtracted from the data.

an effective on-resonance optical depth $d_0 > 50$. The experiment achieves projection-noise-limited sensitivity, as calibrated against a thermal spin state [11].

To account for the spatial variation in the coupling between the probe beam and the trapped atoms, we follow Refs. [21–24] and define an effective atom number N_A such that the expected variance of the coherent spin state $(\Delta \hat{J}_z)^2_C = N_A/4$. For our experimental parameters $N_A = 0.9N_{\text{tot}}$, where N_{tot} is the total number of atoms in the trap, measured via absorption imaging [39].

The measurement sequence is illustrated in Fig. 1(b). For each measurement we prepare a \hat{J}_x -aligned coherent spin state via optical pumping and measure N_A via dispersive atom number measurement (DANM) [36]. We then re-prepare the CSS and make two successive QND measurements to first prepare a conditional spin squeezed state and then verify the noise reduction. We vary N_A from 3.5×10^4 to 7.7×10^5 by briefly switching off the optical dipole trap for 100 μs after each measurement, which reduced the atom number by $\sim 15\%$, and repeating the sequence 20 times per trap loading cycle. At the end of each cycle the measurement is repeated once without atoms in the trap to measure the statistics of $\hat{\phi}_n$. To collect statistics, the entire cycle is repeated 1090 times.

For the DANM measurement we prepare the CSS and stabilize the atomic alignment with a weak magnetic field $B_x = 10 \mu\text{T}$. We then send pulses of circularly polarized light, $\langle \hat{S}_z \rangle = N_L/2$, through the cloud at a detuning of 190 MHz to the red of the $5S_{1/2}(f=1) \rightarrow 5P_{3/2}(f'=0)$ transition with on average $N_L = 1.2 \times 10^6$ photons per pulse, and measure $\langle \hat{S}_y^{(\text{out})} \rangle = G_2 N_L N_A/4$. The QND measurements are made by sending a train of 2 μs long pulses of light with alternating polarization through the elongated cloud at a detuning of 600 MHz to the red of the $5S_{1/2}(f=1) \rightarrow 5P_{3/2}(f'=0)$ transition. Each pulse has on average $N_L = 2 \times 10^8$ photons, except the first pulse, which has $N_L = 1 \times 10^8$ photons. The $G_{1,2}$ coupling constants for the dispersive spin measurements are calibrated in separate experiments [39].

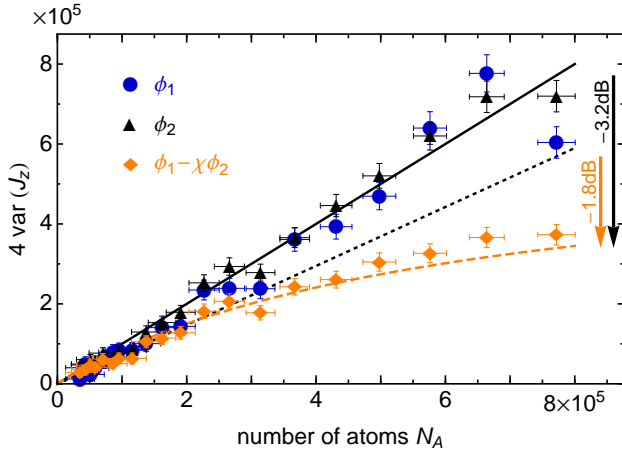


FIG. 3. Noise scaling of the QND measurement of the CSS and spin-squeezed state. Curves are plotted from independently measured experimental parameters. The horizontal and vertical error bars are, respectively, the standard error of the variances and standard deviation of the N_A measurement. The measured read-out-noise has been subtracted from each data set.

The coherence time of the CSS is limited by inhomogeneous magnetic fields along the 8.5 mm length of the cloud. In the ambient magnetic field environment, the coherence lifetime of the CSS is less than 10 μ s. We measure and reduce both homogeneous magnetic fields and the gradient field components to < 0.1 μ T and < 0.2 μ T/cm respectively [40], which extends the coherence time of the CSS to 290 μ s [39].

Figure 2 shows typical correlation plots of the two measurement results, ϕ_1 and ϕ_2 . The read-out noise, measured without atoms in the trap (Fig. 2(a)), is dominated by light shot-noise: we estimate the technical noise contribution to the read-out at -15 dB compared to the light shot-noise with the maximum number of photons, $N_L = 4 \times 10^8$, used in the QND measurement [39]. Measurements of independently prepared coherent spin states (Fig. 2(b)) are uncorrelated, whereas two measurements of the same CSS (Fig. 2(c)) are strongly correlated.

Spin squeezing & entanglement.— To demonstrate spin squeezing, we first verify the projection-noise scaling of the QND measurements. Figure 3 shows the individual variances of the two measurements (blue circles and black diamonds) as a function of N_A . The CSS has an expected variance $(\Delta \hat{J}_z)_C^2 = N_A/4$ (solid black line) that scales linearly with N_A . A quadratic fit, $4 \text{var}(\hat{J}_z) = a_0 + a_1 N_A + a_2 N_A^2$, to the measured data yields $a_1 = 0.99(3)$ and $a_2 = 1.03(3)$ respectively for the two measurements and a_2 coefficients consistent with zero, i.e. no observable atomic technical noise.

A nondestructive measurement of the atomic spin \hat{J}_z projects the initially prepared CSS onto a spin-squeezed state with an uncertainty equal to the measurement pre-

cision. The sensitivity of an ideal optical QND measurement is limited by the shot-noise of the probe light, $\text{var}(\hat{S}'_y) = N_L/2$. We define a signal-to-noise ratio $\zeta = G_1^2 N_L N_A/2$, the ratio of the projection-noise of the CSS to the shot-noise of the light, that determines the predicted noise reduction, $(\Delta \hat{J}_z)_S^2 = (\Delta \hat{J}_z)_C^2/(1+\zeta)$ [41, 42], where the subscripts S and C label the coherent spin and spin squeezed states respectively. We calculate ζ from independently measured experimental parameters (orange dashed line) [39]. For the maximum number of atoms used in the experiment we predict a noise reduction of -3.8 dB with respect to the initial CSS. The observed noise reduction, $\text{var}(\hat{J}_z|\phi_1)$ (orange diamonds), is slightly smaller, -3.2 dB relative to the expected variance $(\Delta \hat{J}_z)_C^2 = N_A/4$, consistent with experimental uncertainties.

Quantum noise reduction alone does not imply spin squeezing; the QND measurement must also preserve coherence. In an atomic ensemble with finite optical depth, photon scattering during the QND measurement reduces the alignment of the CSS: $\langle \hat{J}_x \rangle_C \rightarrow \langle \hat{J}_x \rangle_S = (1 - \eta_{sc})\langle \hat{J}_x \rangle_C$, where η_{sc} is the probability that an atom loses coherence. For the photon number, $N_L = 3 \times 10^8$, used in the first QND measurement we measure $\eta_{sc} = 0.11$ [39]. In addition, magnetic field inhomogeneities dephases the CSS between the two QND measurements, reducing the \hat{J}_x -alignment by a factor $\eta_{dep} = 0.034$.

To verify spin squeezing we use the Wineland criterion: if $\xi_m^2 \equiv (\Delta \hat{J}_z)_S^2 N_A / |\langle \hat{J}_x \rangle_S|^2$, then $\xi_m^2 < 1$ guarantees metrological advantage in using the spin-squeezed state over a CSS with equivalent polarization [1]. We satisfy the Wineland criterion if the conditional variance of the spin-squeezed state is less than the projection-noise of the CSS times $(1 - \eta_{sc})^2(1 - \eta_{dep})^2$ (black dotted line in Fig. 3). For the maximum number of atoms used in the experiment we infer $\xi_m^2 = 0.66$, giving -1.8 dB of metrologically significant spin squeezing. Furthermore, the observed quantum noise reduction of -3.2 dB and the measured \hat{J}_x -alignment of the spin-squeezed state, $\langle \hat{J}_x \rangle_S = 0.86\langle \hat{J}_x \rangle_C$, are sufficient to demonstrate entanglement among the spin-1 atoms [3].

Conclusion.— Using dynamically-decoupled quantum non-demolition measurements in an ensemble of up to 8.4×10^5 laser-cooled ^{87}Rb atoms, we have produced and detected spin-squeezed states in an $f = 1$ atomic system. The probing technique, which cancels decoherence due to tensorial light shifts, can be applied to arbitrarily large spins, and extends measurement-induced squeezing beyond real and effective two-level systems. Compensation of magnetic field gradients along the 8.5 mm length of the ensemble extend the lifetime of the magnetically sensitive coherent spin state to 290 μ s. We demonstrate -3.2 dB of quantum noise reduction and -1.8 dB of metrologically-relevant spin squeezing, consistent with theoretical models and limited by the optical depth of the ensemble and dephasing due to residual magnetic field

inhomogeneity. This latter effect, accounting for 0.3 dB, could be recovered by spin-echo techniques. Potential applications include optical magnetometry [25, 30], quantum networking [6], and the study of exotic phases in degenerate spinor gases [26–28].

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* robert.sewell@icfo.es; <http://www.mitchellgroup.icfo.es/>

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